New Physics at the Tevatron
(a few selected topics)

Carlos E.M. Wagner

Argonne National Laboratory
EFI, University of Chicago

Mini-Symposium on Physics at the Tevatron
EFI, Univ. of Chicago,
March 5, 2004

Selection of Topics

- Light stops: Motivation and searches at the Tevatron collider.

  R-Parity conserving models : Pair production
  Dark matter and the stop-neutralino mass difference.

  R-Parity violating models: Single stop production

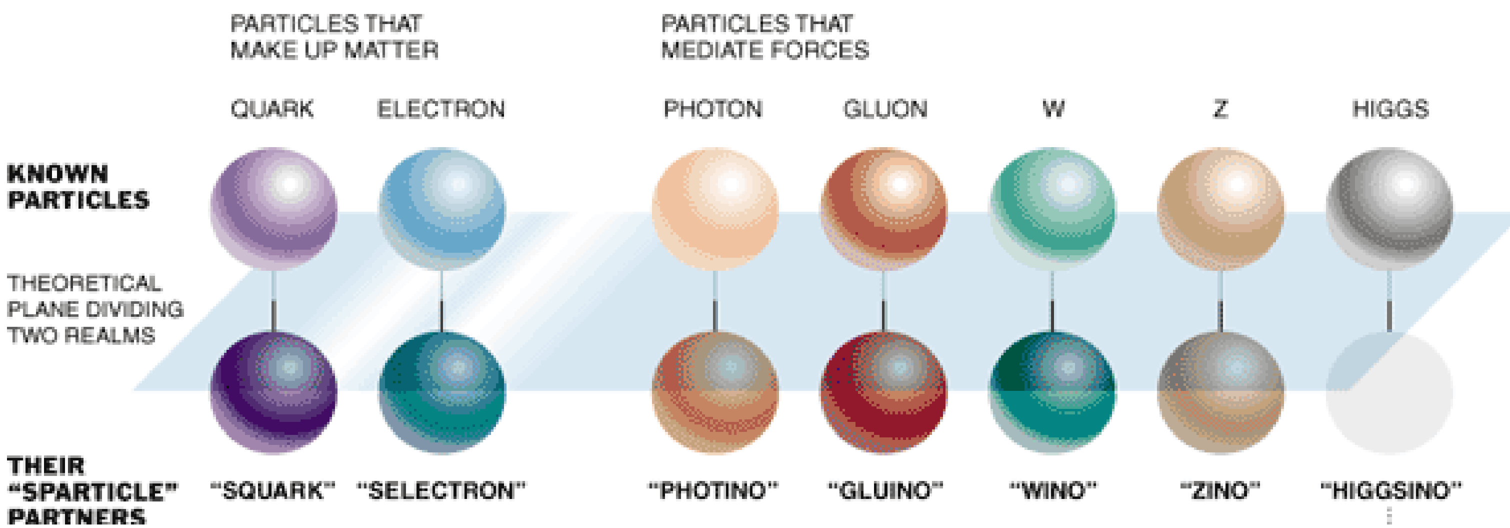
- Photon signatures in low-energy supersymmetry breaking models

- Light sbottoms and gluinos: Motivation and signatures

- Heavy quarks: Motivation and signatures
  Higgs searches

supersymmetry

fermions ⟷ bosons



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)

Why Supersymmetry ?

- Helps to stabilize the weak scale—Planck scale hierarchy

- Supersymmetry algebra contains the generator of space-time translations.
  Necessary ingredient of theory of quantum gravity.

- Minimal supersymmetric extension of the SM :
  Leads to Unification of gauge couplings.

- Starting from positive masses at high energies, electroweak symmetry breaking is induced radiatively.

- If discrete symmetry, $P = (-1)^{3B+L+2S}$ is imposed, lightest SUSY particle neutral and stable: Excellent candidate for cold Dark Matter.

Light Stops: Motivation

- In low energy supersymmetry models, light stops are induced as a consequence of large mixing or large negative radiative effects.
- They are required for the realization of the mechanism of electroweak baryogenesis in the MSSM
- Signatures of a light stop at the Tevatron collider depend strongly on the chargino and neutralino spectrum as well as on the nature of supersymmetry breaking

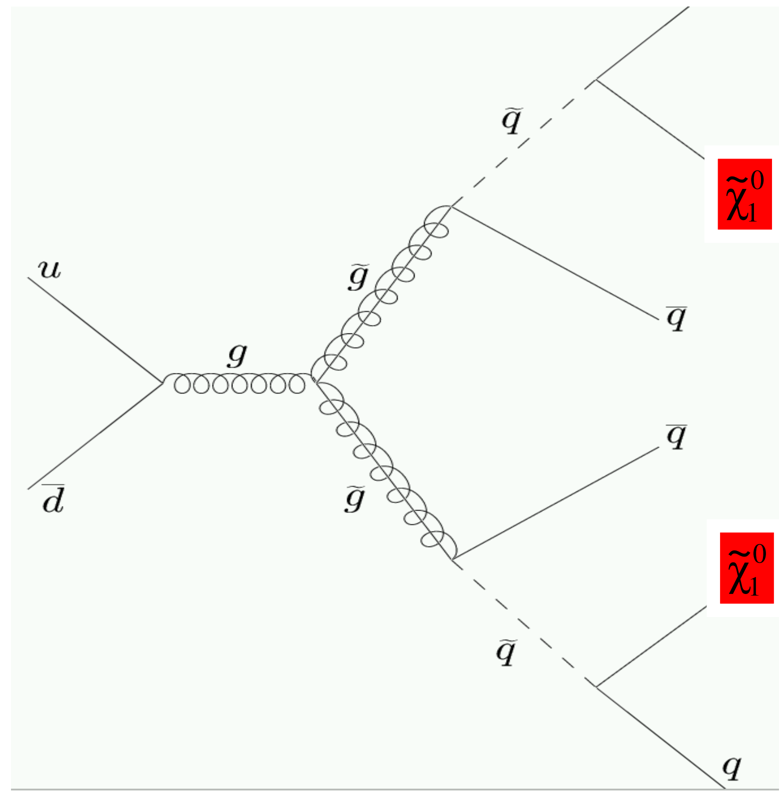
Supersymmetry at colliders

Gluino production and decay: Missing Energy Signature

Supersymmetric Particles tend to be heavier if they carry color charges.

Particles with large Yukawas tend to be lighter.

Charge-less particles tend to be the lightest ones.



- **Lightest supersymmetric particle = Excellent Cold dark matter candidate.**

Stop mass matrix

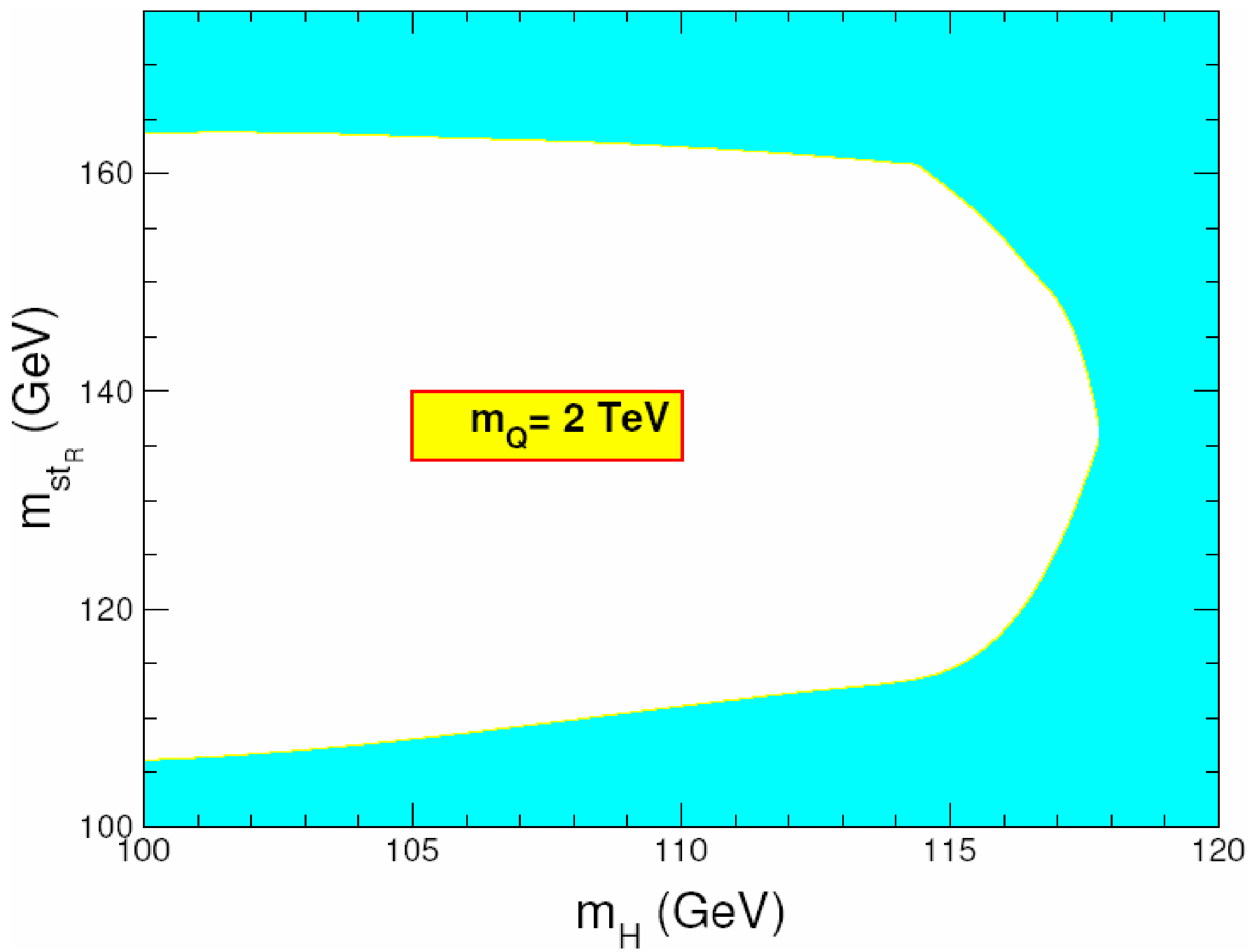
- Radiative corrections affect mostly the hierarchy of diagonal masses in stop mass matrix

$$M^2 = \begin{bmatrix} \mathrm{m}_{\mathrm{Q}}^2 + \mathrm{m}_{\mathrm{t}}^2 & \mathrm{m}_{\mathrm{t}}\,(\mathrm{A}_{\mathrm{t}} - \mu\ \mathrm{cotan}\beta) \\ \mathrm{m}_{\mathrm{t}}\,(\mathrm{A}_{\mathrm{t}} - \mu\ \mathrm{cotan}\beta) & \mathrm{m}_{\mathrm{U}}^2 + \mathrm{m}_{\mathrm{t}}^2 \end{bmatrix}$$

- Large stop mixing induced by off-diagonal elements in stop mass matrix

Higgs and Stop mass limits
Electroweak baryogenesis

Carena, Quiros, C.W. '98



Tevatron Stop Reach for charginos lighter than stops

Dominant channel always that two body decay of stop into chargino is open : $m_{\tilde{t}} > m_b + m_{\tilde{\chi}^+}$

Signatures similar to top pair production:

b + l + jets + miss. E

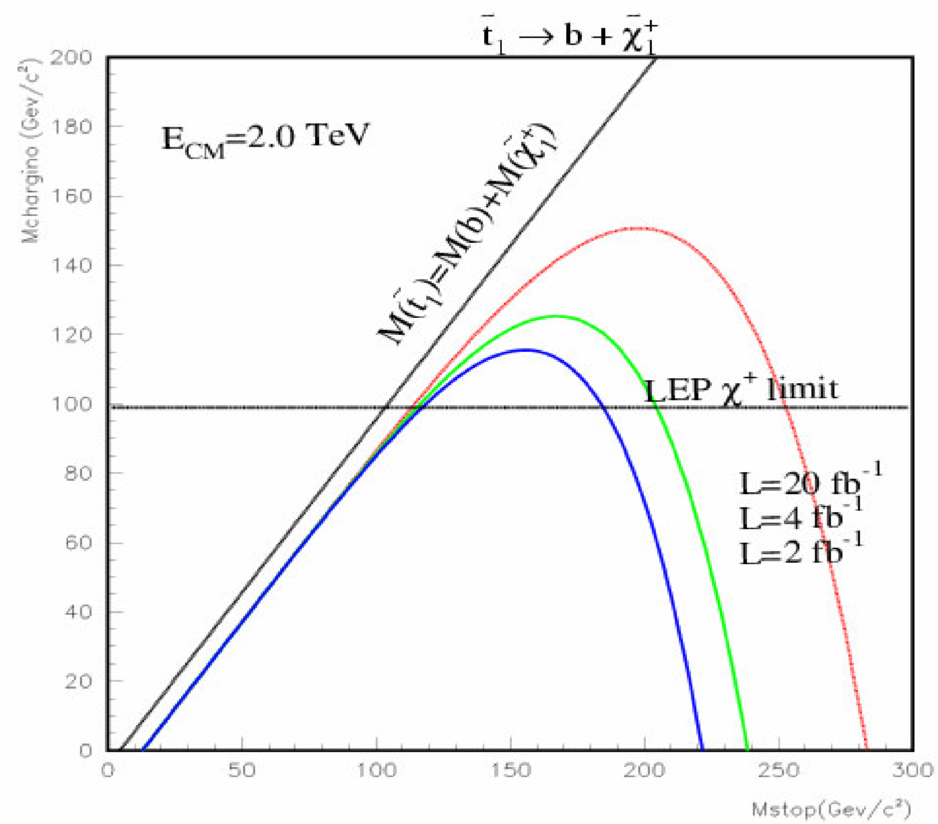
Isolated lepton with $p_T > 10$ GeV

Two jets with $E_T > 12, 8$ GeV

One of the jets b-tagged

No isolated lepton pairs

Missing $E_T > 25$ GeV



Demina, Lykken, Matchev,Nomerotsky '99

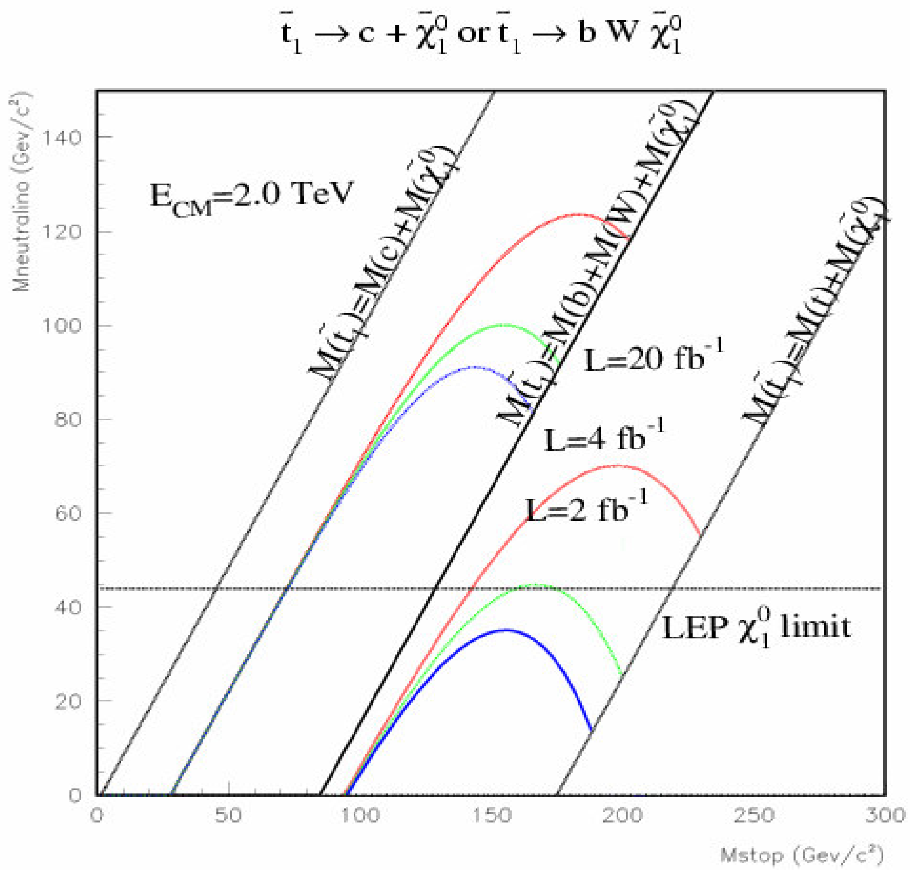
Tevatron Stop Reach when two body decay channel is dominant

Main signature:

2 or more jets plus missing energy

2 or more Jets with $E_T > 15$ GeV

Missing $E_T > 35$ GeV



Demina, Lykken, Matchev,Nomerotsky '99

Stop-Neutralino Mass Difference: Information from the Cosmos

- If the neutralino provides the observed dark matter relic density, then it must be stable and lighter than the light stop.

- Relic density depends on size of neutralino annihilation cross section.

  If only stops, charginos and neutralinos are light, there are three main annihilation channels:

1. Coannihilation of neutralino with light stop. Small mass difference.
2. s-channel annihilation via light CP-even Higgs boson
3. s-channel annihilation via heavy CP-even Higgs boson and CP-odd Higgs boson

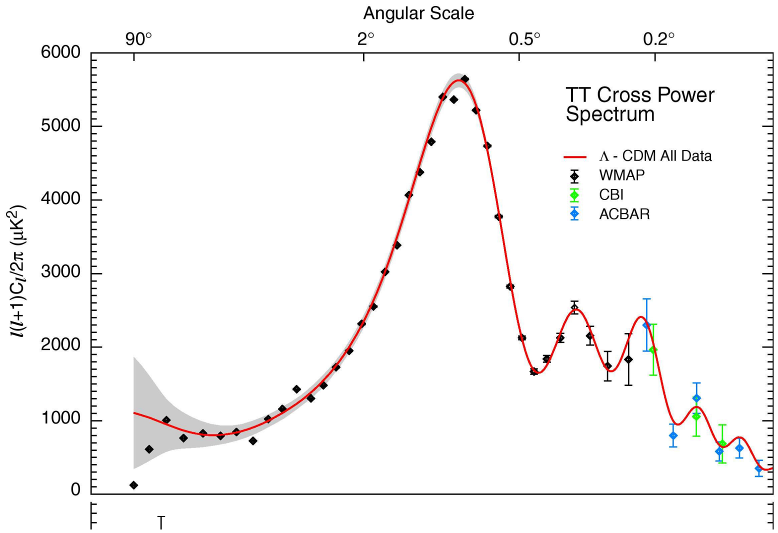
Cosmic Microwave Background WMAP

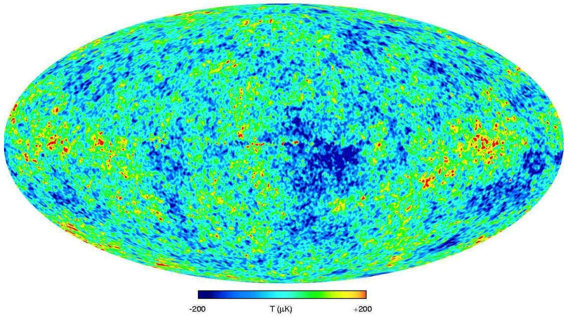
h=0.71±0.04

$\Omega_M h^2$=0.135±0.009

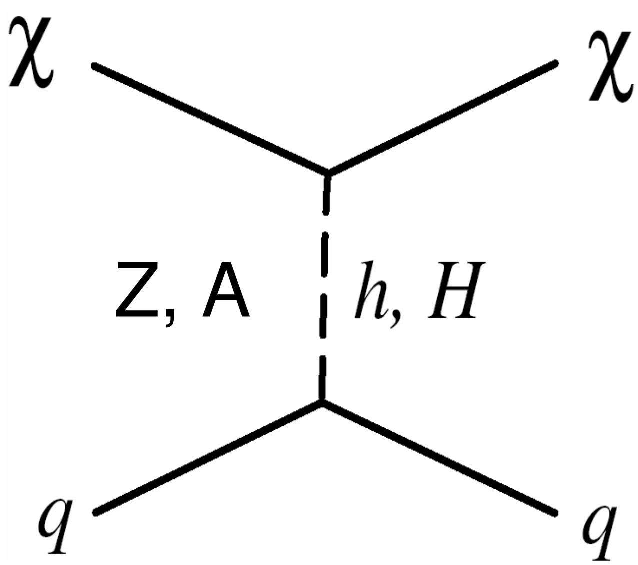
$\Omega_B h^2$=0.0224±0.0009

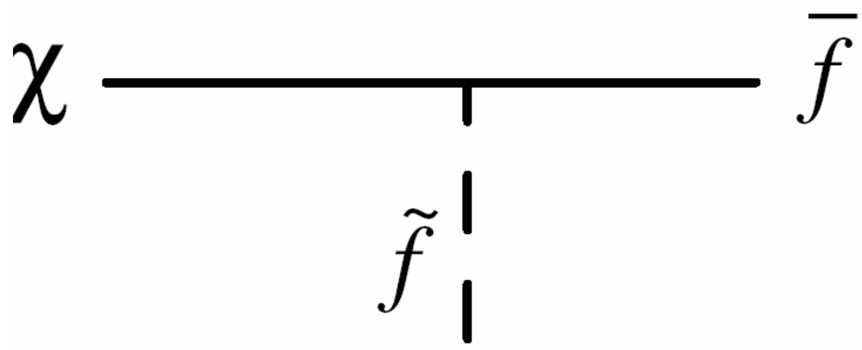
Ω_{tot}=1.02±0.02





Main Annihilation Channels





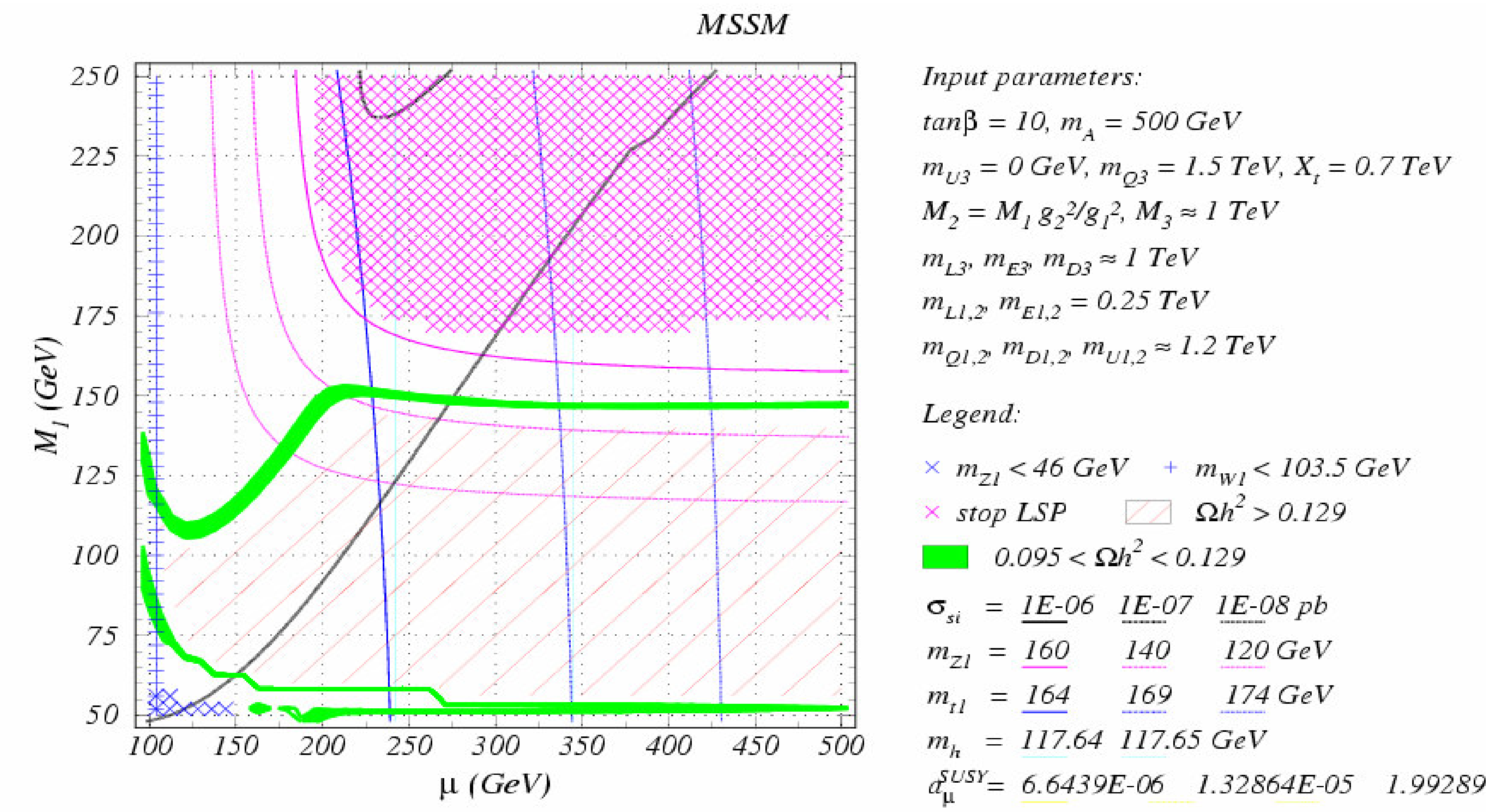
Z channel annihilation into any quarks and leptons

Higgs channel annihilation mostly into bottom quarks

Due to enhanced couplings, H-induced cross section much larger than h-induced one ($\tan^2\beta$ enhancement)

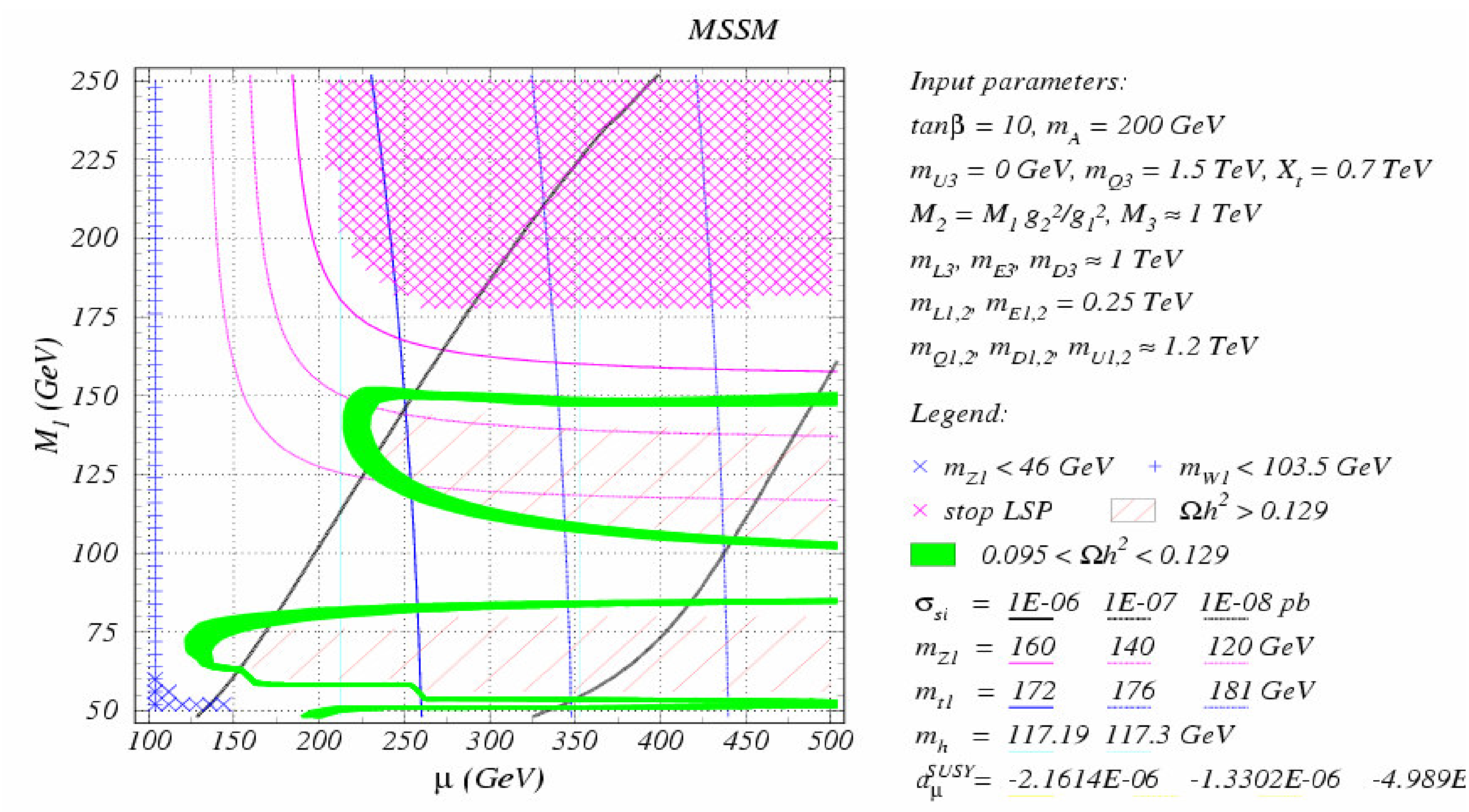
Light Stops and Dark Matter in the MSSM

Carena, Balazs and C.W. ‘04



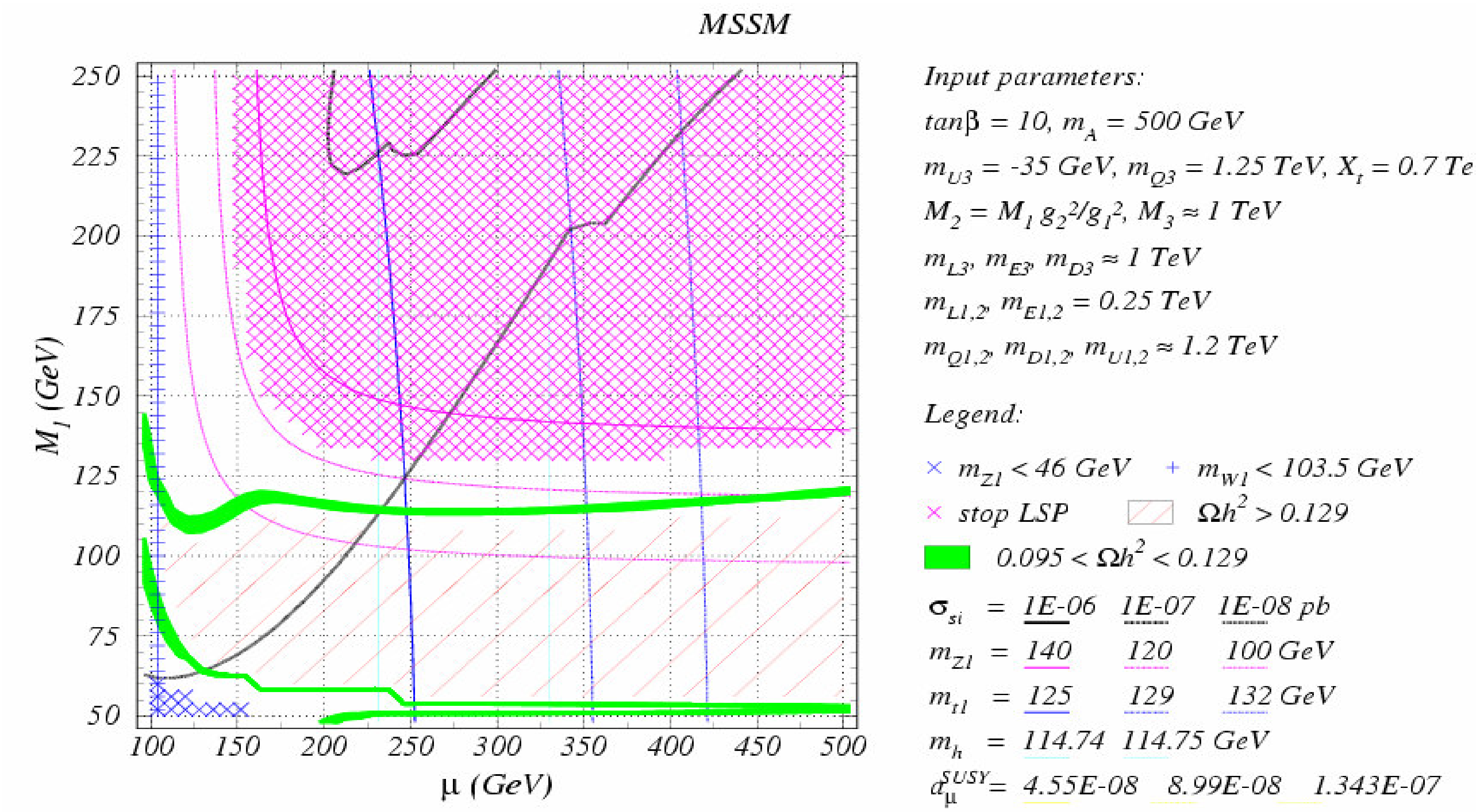
Light Stop and Dark Matter for small values of the CP-odd Higgs mass

Carena, Balazs and C.W. '04



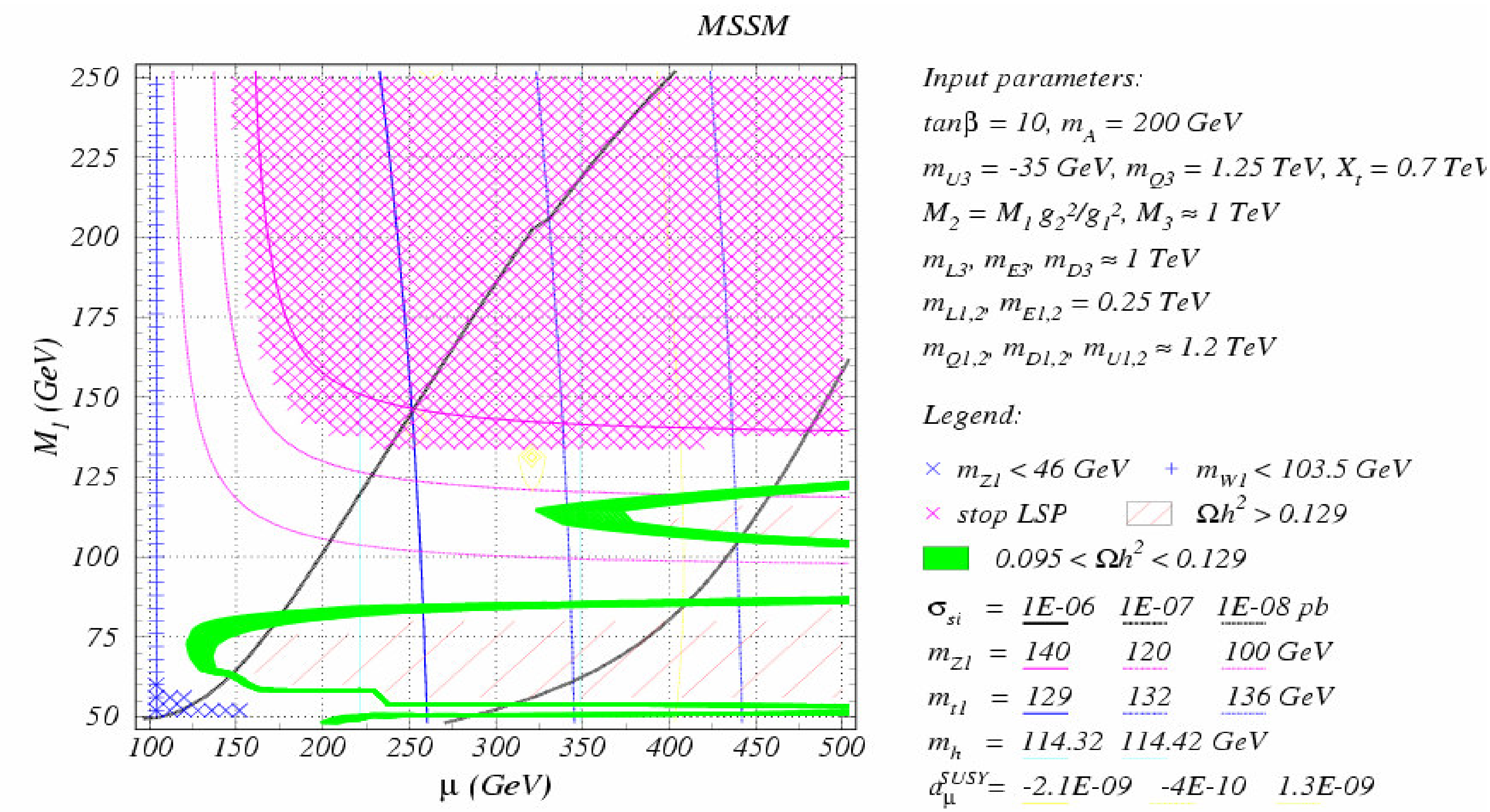
Light stop and Dark Matter

Carena, Balazs and C.W. '04



Light stops and Dark Matter for small values of CP-odd Higgs mass

Carena, Balazs and C.W. '04



Searches of light stop plus neutralino dark matter

- Stop-neutralino coannihilation region difficult due to reduced cross section or small stop-neutralino mass difference

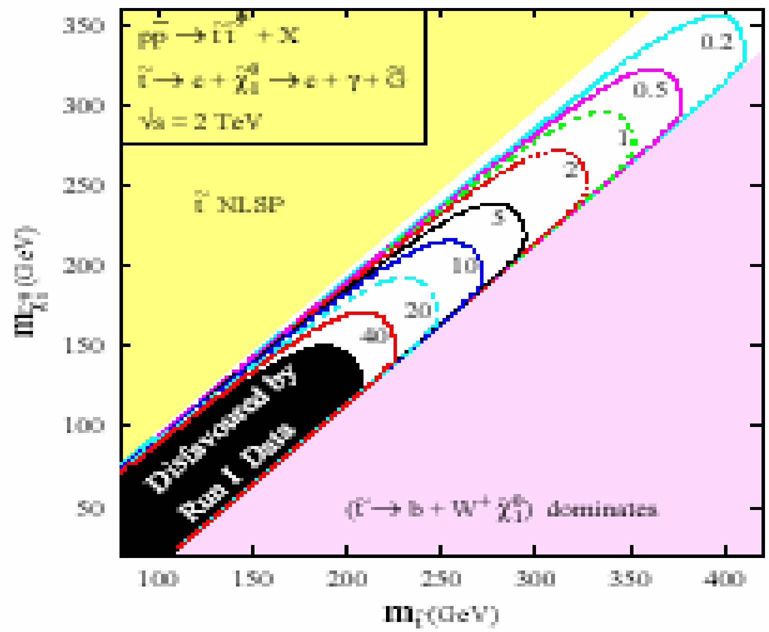
- s-channel Higgs or Z annihilation regions simpler, so far two-body decay dominant

- In region where s-channel annihilation via lightest CP-even Higgs, trilepton channel open (Test chargino masses up to 130 GeV)

Tevatron stop searches in low-energy SUSY breaking models

Carena, Choudhury,Diaz, Logan and C.W. ‘02

Extra photon and large missing energy helpful in stop detection



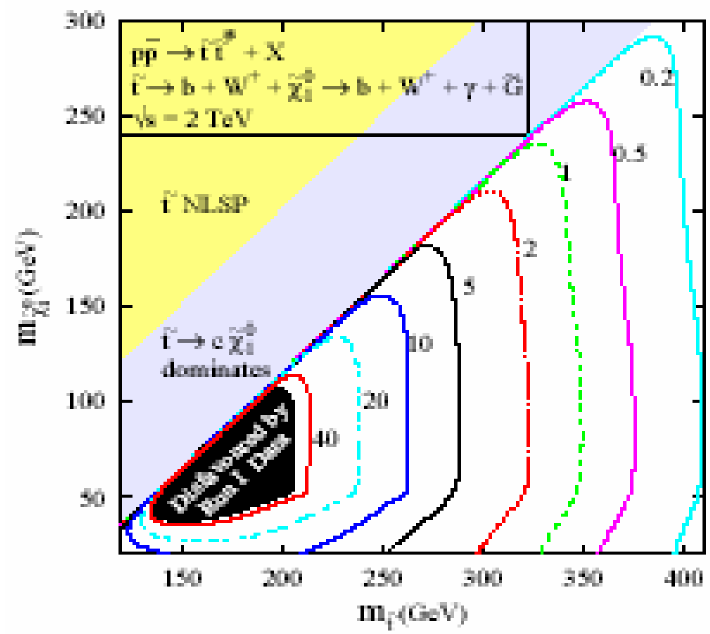
Cross sections for stop pair production in fb, with $\tilde{t} \longrightarrow c\gamma\tilde{G}$ and Signal/selection $jj\gamma\gamma \not{E}_T$

$\int \mathcal{L}$	σ_S 5σ	Max. $m_{\tilde{t}}$ (2 body)
2 fb^{-1}	6 fb	290 GeV
4 fb^{-1}	3.5 fb	315 GeV

Tevatron stop searches in low-energy SUSY breaking models

Carena, Choudhury,Diaz, Logan and C.W. ‘02

Extra photon and large missing energy helpful in stop detection



Cross sections for stop pair production in fb, with $\tilde{t} \to bW\gamma\tilde{G}$ and Signal/selection $bbWW\gamma\gamma \not{E}_T$

$\int \mathcal{L}$	σ_S	Max. $m_{\tilde{t}}$ (3 body)
2 fb^{-1}	2.5 fb	315 GeV
4 fb^{-1}	1.3 fb	330 GeV

R-Parity breaking scenario

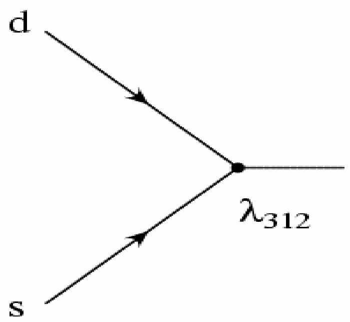
- Relevant interactions:
  Baryon number violating ones

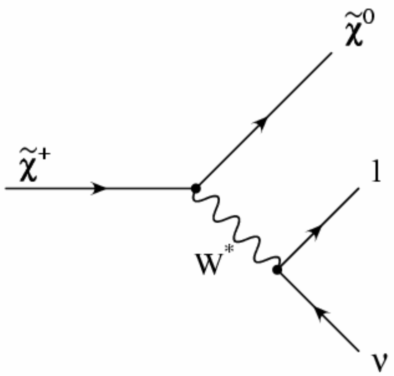
$$W_{\mathrm{R.P.B.}} = \lambda''_{ijk}\ \mathrm{U}_{\mathrm{i}}\,\mathrm{D}_{\mathrm{j}}\,\mathrm{D}_{\mathrm{k}}$$

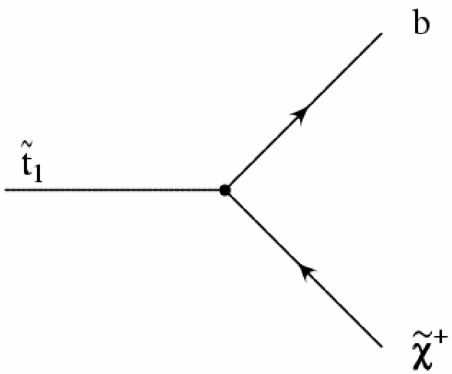
- An up-squark interacts with two down-quarks.
  i,j,k are generation indeces.

- Color contraction implies that down-quark generation indeces must be different.
  Stop : i = 3.

Dominant production and decay modes



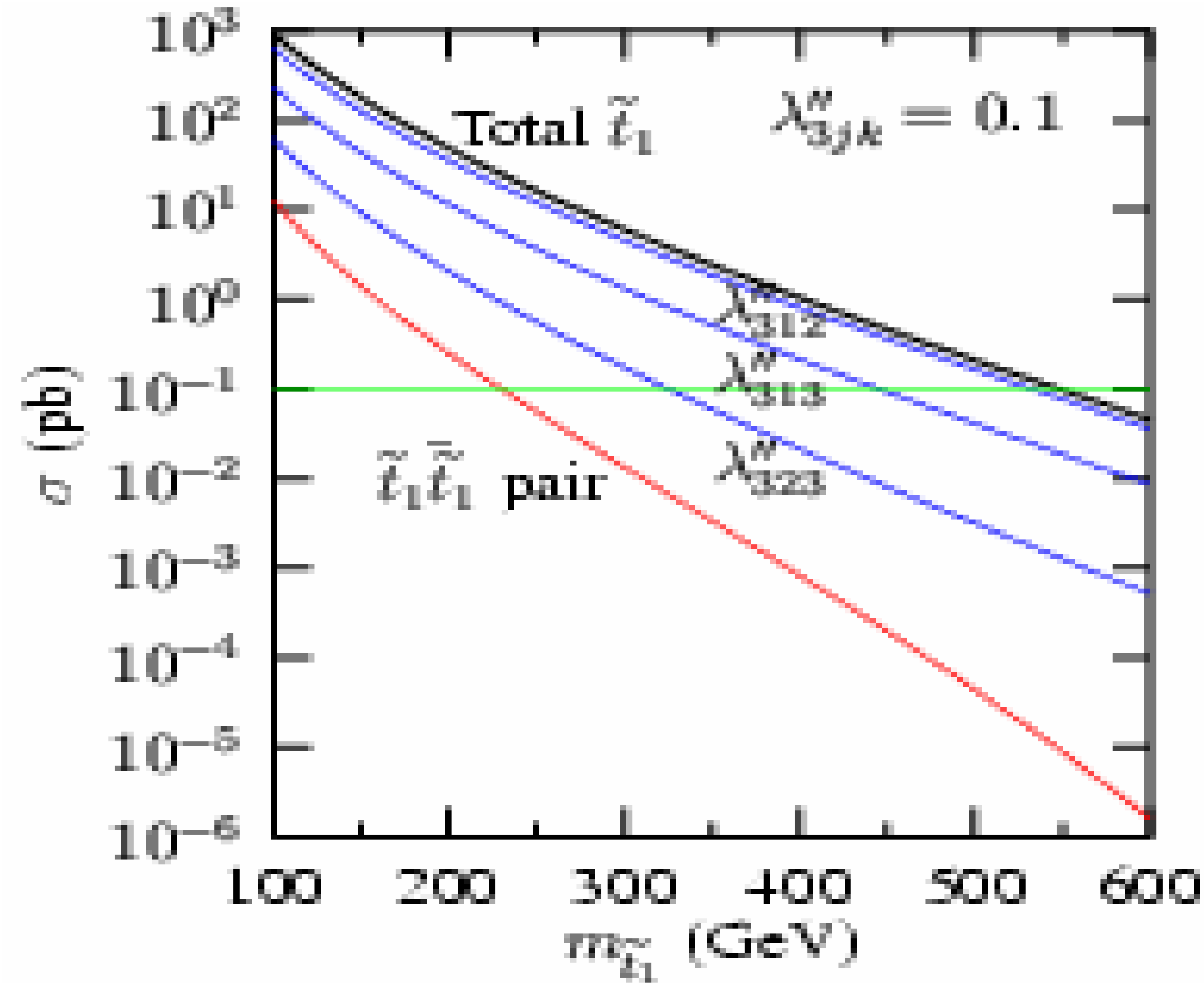




For relevant production rates, dominant decay is either into R-Parity violating modes, or into a bottom and a chargino

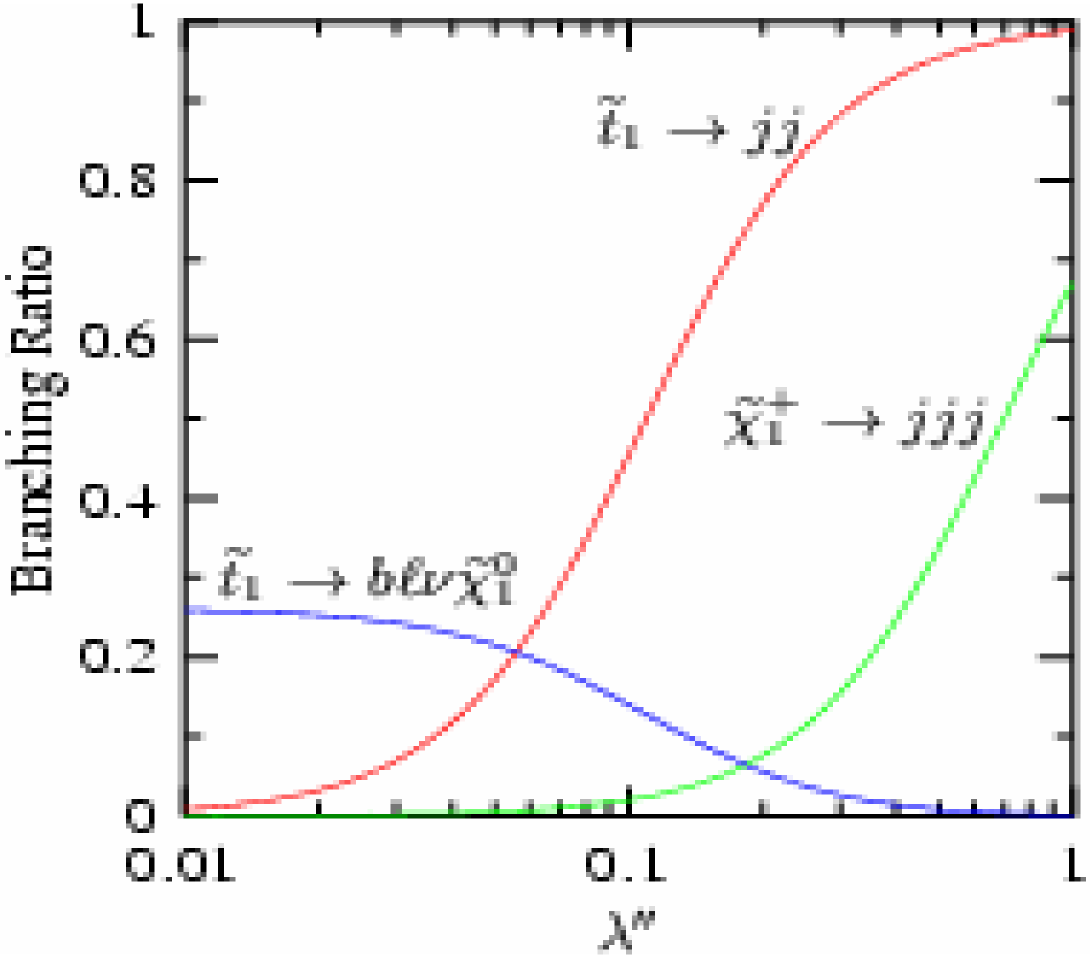
Cross section for stop production in the presence of R-Parity violation

Berger, Harris and Sullivan '01



Branching Ratio of Stop decays

Berger, Harris and Sullivan '01



Search Strategy

- Only R-parity conserving decay searched for, with leptons in final state. Cross section increases with R-Parity violating coupling, but Branching Ratio decreases

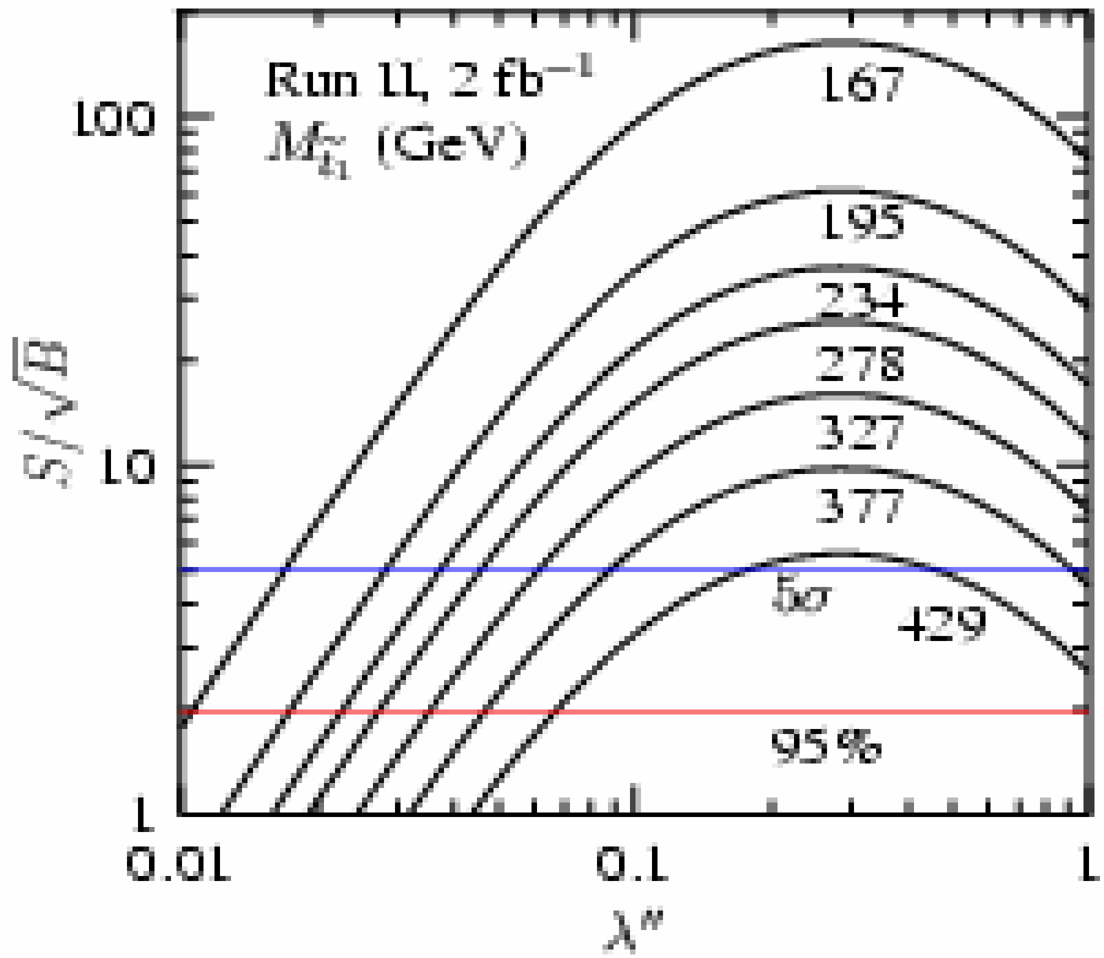
- Signal for stop production is b + l + Miss. Energy

- Large backgrounds from W + jet production and single top

- Mass peak reconstructed with mass definition $\mathrm{M_T^{bl} + Miss.\,Energy}$ which is centered at $\mathrm{m}_{\tilde{\mathrm{t}}} - \mathrm{m}_{\tilde{\chi}} + 5\,\mathrm{GeV}$

Stop reach with R-Parity violation

Berger, Harris and Sullivan '01

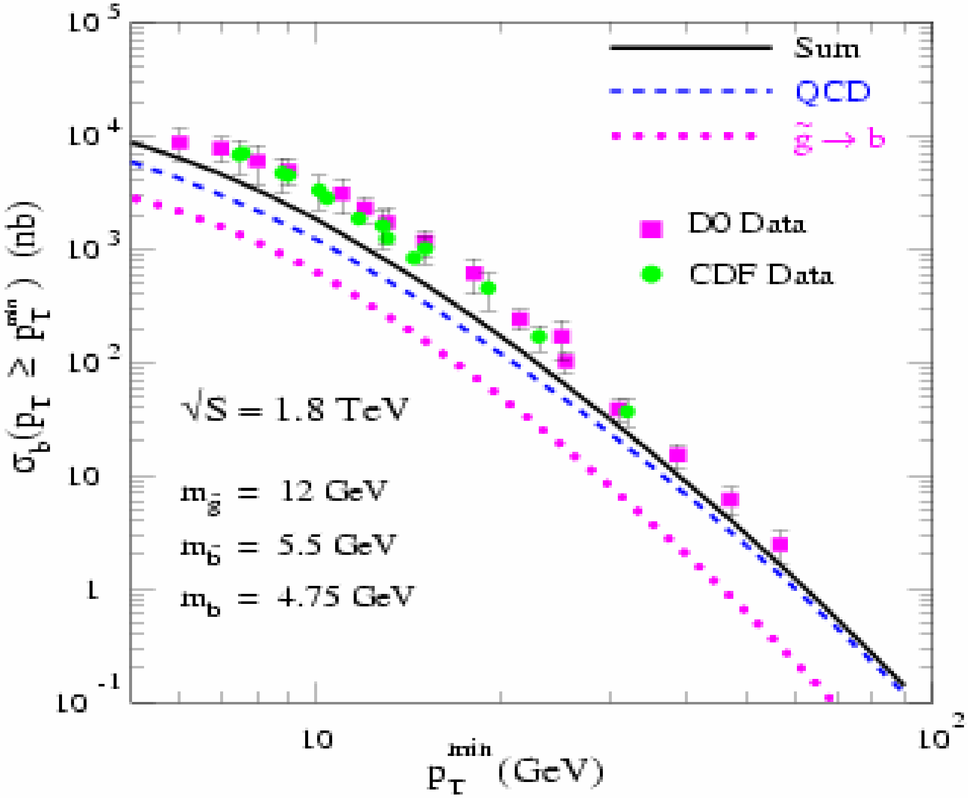


Stops with masses up to 350 GeV may be easily discovered at the Tevatron collider

Light Sbottom and Light Gluinos

Motivation: Discrepancy between Theory and Experiment in inclusinve bottom-quark cross section.

Berger, Harris, Kaplan, Sullivan, Tait, Wagner '01

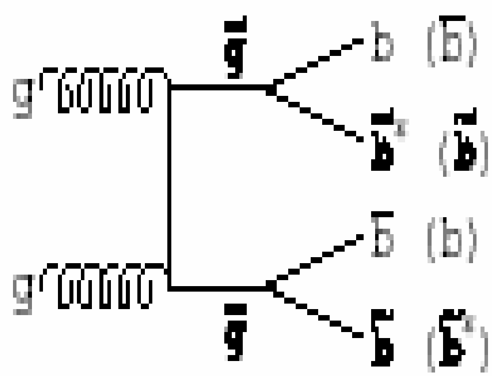


Extra bottom-quarks obtained from gluino decays !

Gluinos are Majorana Particles

Gluinos can decay either into bottom or antibottoms at equal rates.

Equal sign bottom-quark pairs at production level



Equal bottom-quark pairs in SM

- Obtained from oscillations between different B-meson states

- Total value of time integrated mixing probability is such that measured at lepton colliders to be close to

$$\chi \quad = \quad 0.118 \ \pm 0.005$$

- Here $2\chi\left(1-\chi\right)$ is the amount of equal sign bb pairs.

- Prediction at Tevatron collider

$$\chi \quad = \quad 0.160 \ \pm 0.020$$

Berger, Harris, Kaplan, Sullivan, Tait, Wagner '01

- Recent CDF measurement

$$\chi \quad = \quad 0.152 \ \pm 0.007 \ \pm 0.011$$

hep-ex/0309030

New Heavy Quarks

- Motivation: Arrange the difference between value of weak mixing angle obtained from lepton and hadron asymmetries at LEP and SLD
- New heavy mirror quarks, with the same quantum numbers as doublet of quarks and right-handed down quark, with relevant mixing with third generation quarks in the right-handed currents
- Masses constrained to be below 300 GeV, with top-prime quark mass being 0.8 times the bottom-prime mass.

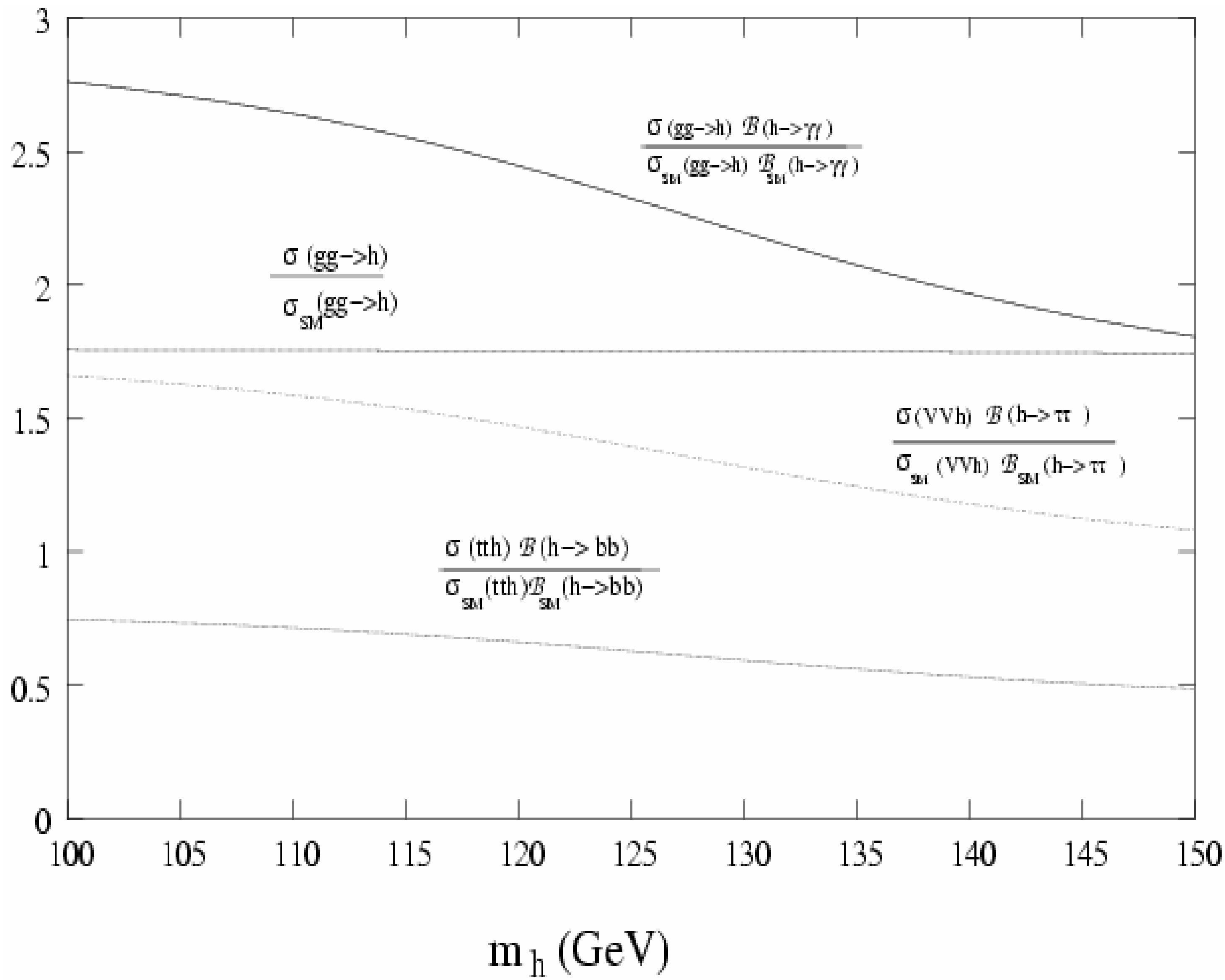
Choudhury, Tait, C.W. ‘02

Bottom-quark -- Heavy Quark Mixing Effects

- Most relevant implications in Higgs physics
- Effective bottom-quark Yukawa coupling reduced by about 20 percent. For light Higgs bosons, branching ratio of decay into tau leptons increased.
- New loop contributions in gluon fusion diagram, increase Higgs production cross section.
  Particularly important for Higgs searches in W W and tau lepton pair modes

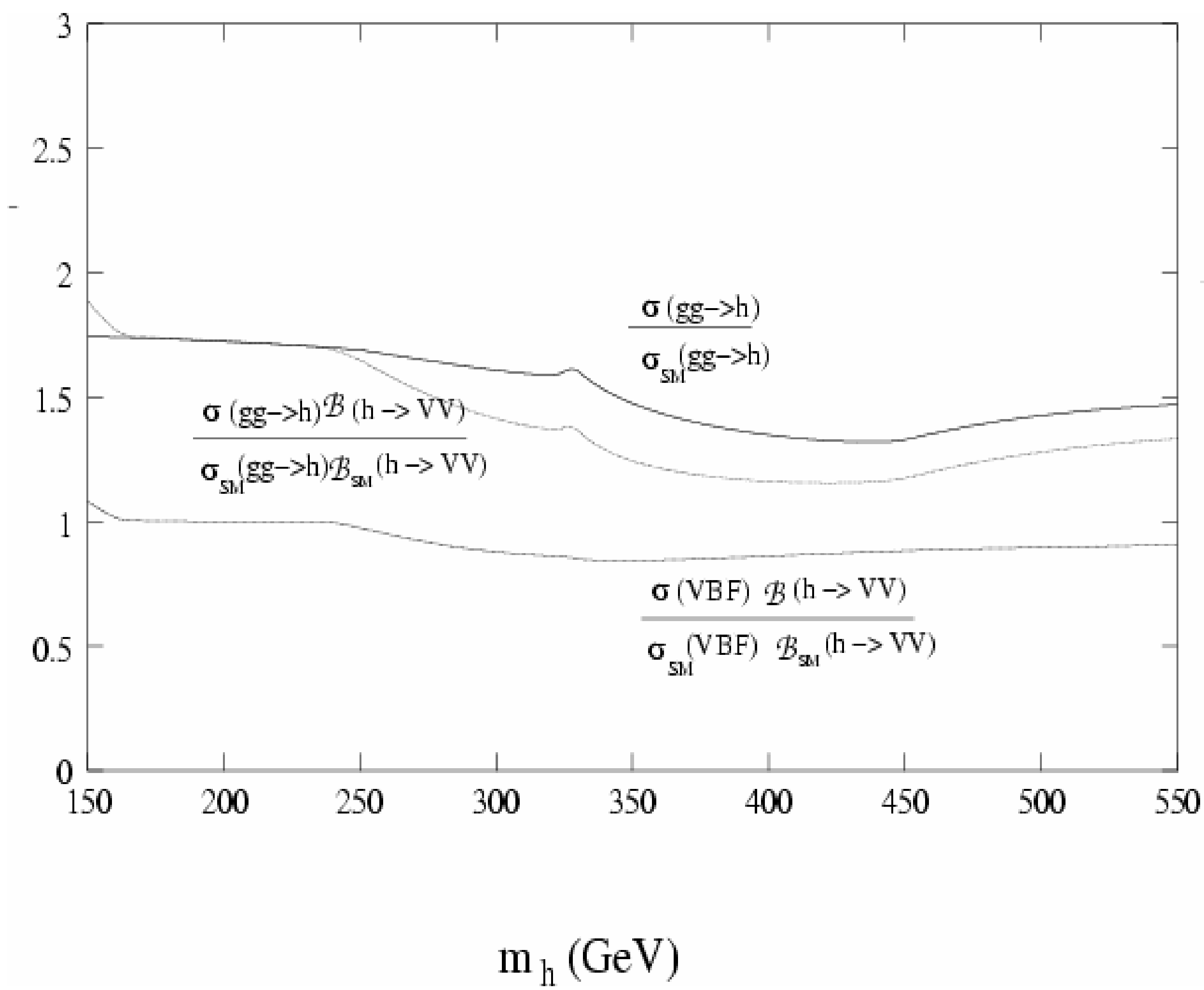
Most relevant Higgs production modes

Morrissey
and C.W. ‘03



Production mode for heavy Higgs bosons

Morrissey and C.W. '03

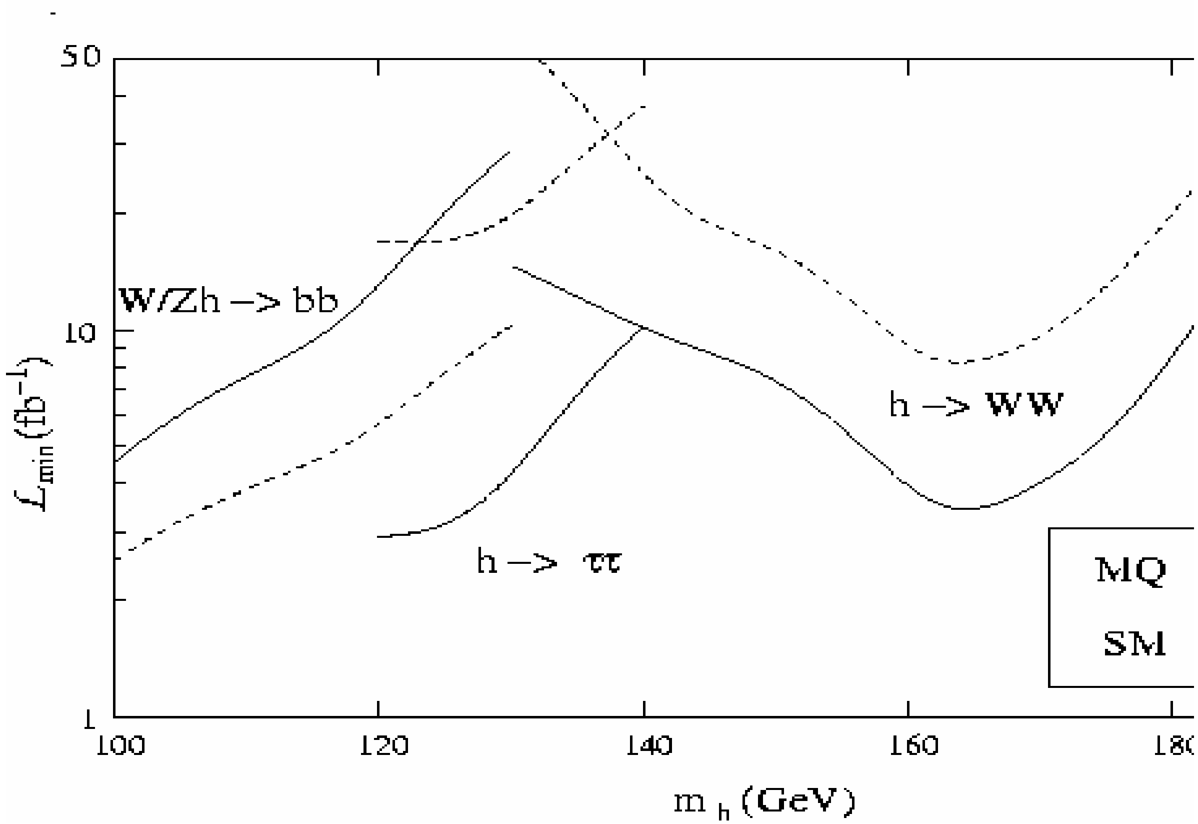


Luminosity required for a 3 sigma evidence of a Higgs boson at the Tevatron collider

Tau-lepton channel becomes dominant in low mass region.

Solid line: With extra quarks.   Dahsed line: SM

Morrissey and C.W. '03



Results make use of Tevatron Higgs study and of Belyaev, Han, Rosenfeld '03.

Search for heavy quarks at the Tevatron

- Top prime has a mass below 250 GeV.
- Bottom prime has a mass below 300 GeV.
- Since bottom-prime is heavier than top-prime and due to large mixing, dominant decay mode of top-prime is into a W and a b

$$t^{'} \to b\,W^{+}$$

- Similar to top quark searches. Top: Irreducible background. Top-prime must be looked for in the top data.
- Based on simple counting experiment

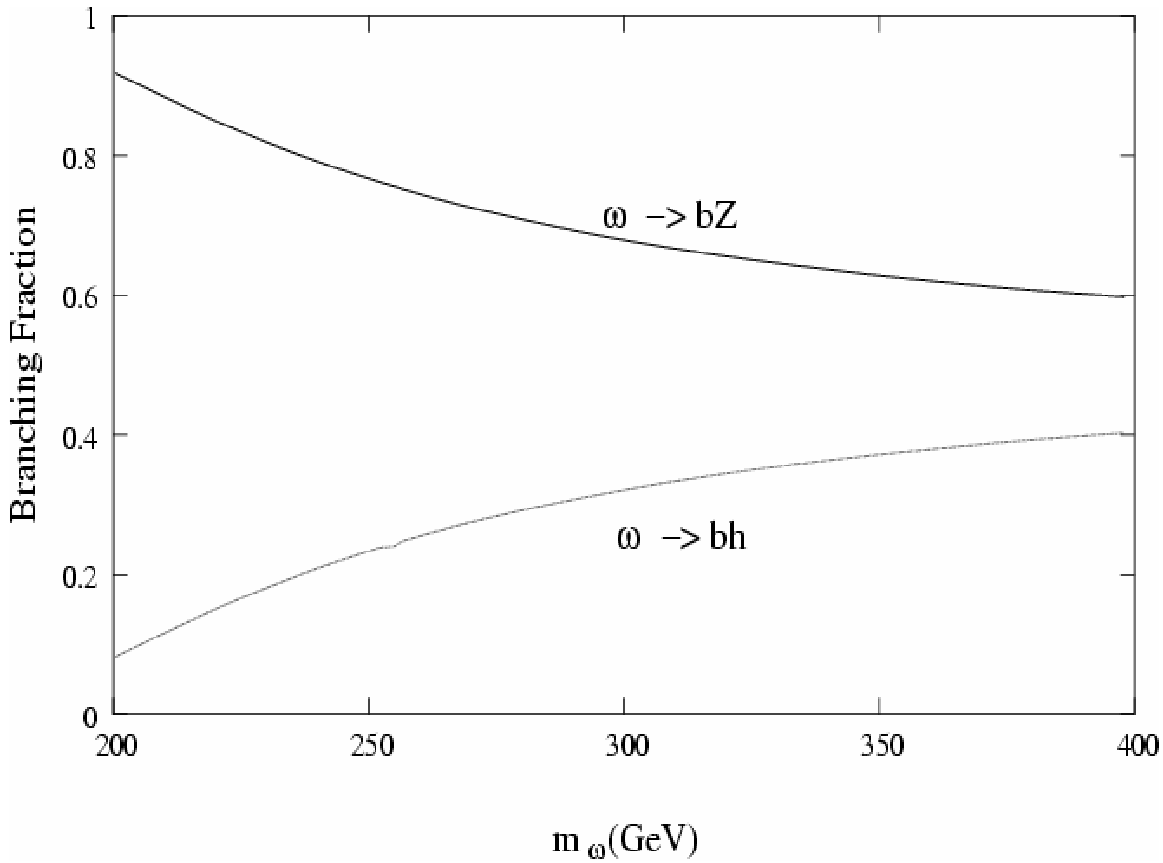
$$\mathrm{m}_{t^{'}} < 250\,\mathrm{GeV} \quad \mathrm{with}\ \ 4\,\mathrm{fb}^{-1}$$

Decay of modes heavy bottom-prime ω

- Due to large mising, bottom-prime decay mostly into Z-gauge bosons and bottom-quarks.

Morrissey
and C.W. '03

$m_h = 170\,\mathrm{GeV}$



Reach of Tevatron Collider

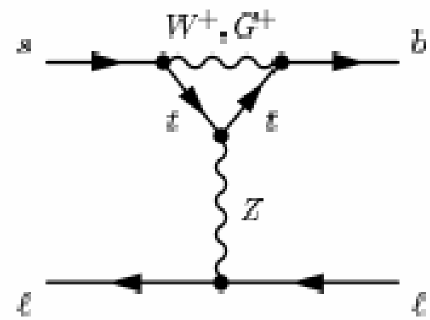
- Bottom-prime have been searched for in decays into Z and b-quarks. Present limit: 200 GeV
- Estimates base on extrapolation of Run I analysis show that Tevatron with 4 inverse fb can discover such quarks up to masses

$$\mathrm{m}_{\omega} < 300\,\mathrm{GeV}$$

- Detailed analysis of signal and background has been done by Troy and Rosner '03, with similar results.

$B_s \to \mu^+\mu^-$ as a probe of $\tan\beta$ at the Tevatron

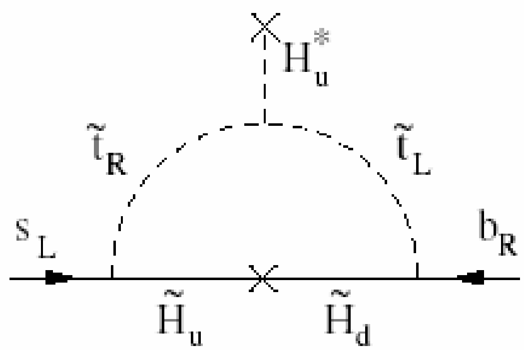
SM sample diagram:



SM amplitude $\propto \; V_{ts} \frac{m_\mu}{M_W}$

$Br(B \to \mu^+\mu^-)_{\rm SM} = (3.8 \pm 1.0) \times 10^{-9}$

- In the MSSM, with two Higgs doublets, the Higgs Mediated contribution can put this BR at the reach of the Tevatron!



After SUSY breakdown, new contributions to d-type quark masses are generated even in a Minimal Flavor Model (CKM-induced)

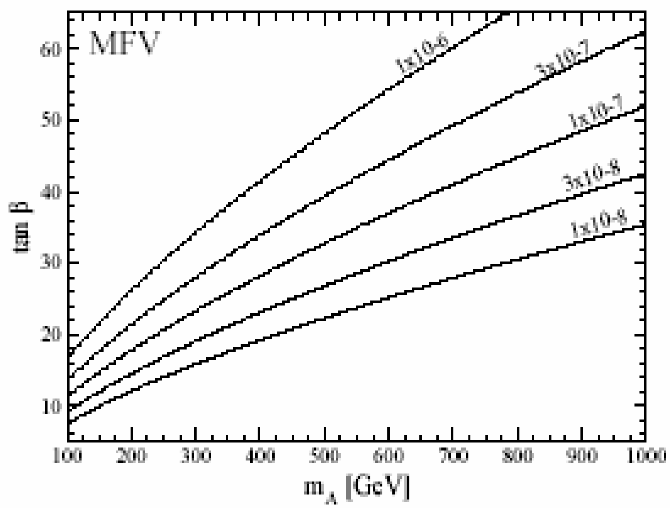
$Br(B \to \mu^+\mu^-)_{\rm MSSM} \propto \tan^6\beta \frac{1}{M^2_{A^0}} f(\mu A_t, M_{\tilde{t}_i}, M_{\tilde{\chi}_i^+})$

where $f \to$ const. $\neq 0$ for $M_{\rm SUSY} \to \infty$.

Babu, Kolda

$\Rightarrow$ branching fraction can be enhanced by three orders of magnitude!

Contours of Maximun allowed value of BR($B_s \to \mu\mu$) as a function of M_A and $\tan\beta$.



- $Br(B_s \to \mu^+\mu^-) < 2.6 \cdot 10^{-6}$ from Run 1.
- Single event sensitivity at Run 2 is 10^{-8} for 2 fb^{-1}

Kane, Kolda, Lennon

If a signature is observed at the Tevatron $\Longrightarrow$ lower bound on the value of $\tan\beta$

$$\tan\beta > 11 \left(\frac{M_A}{100GeV}\right)^{2/3} \left[\frac{Br(B_s \to \mu^+\mu^-)}{10^{-7}}\right]^{1/6}$$

Interesting to study direct reach in M_A via $b\bar{b}$ A/H production for large $\tan\beta$ and reach in $Br(B_s \to \mu^+\mu^-)$ for different sets of MSSM parameters

Conclusions

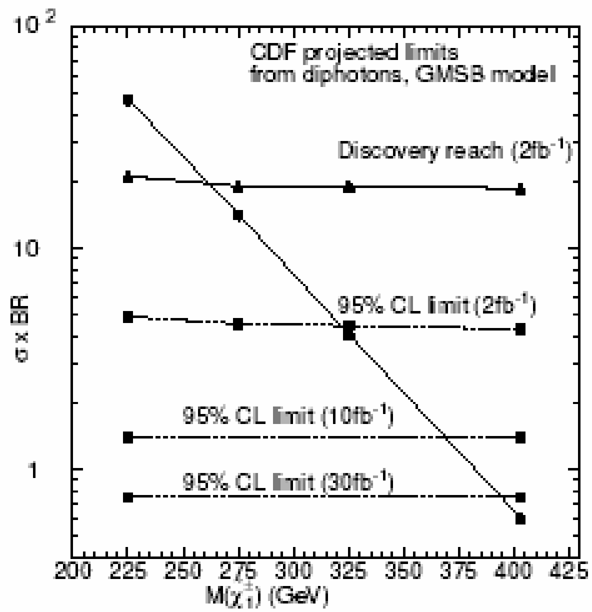
- Tevatron is exploring the higher energy frontier available up to now in particle physics experiments
- Many interesting models predict signatures of new physics at the Tevatron collider
- In most cases, relevant signals demand at least one inverse fb, showing that things may become very exciting in the years to come

Gauge-Mediated Tevatron Reach

- Bino-like NLSP: $\tilde{\chi}_1^0 \to \gamma \tilde{G}$

  Signal: $\gamma\gamma X \not\!\!E_T$

  $X = \ell$'s and/or jets



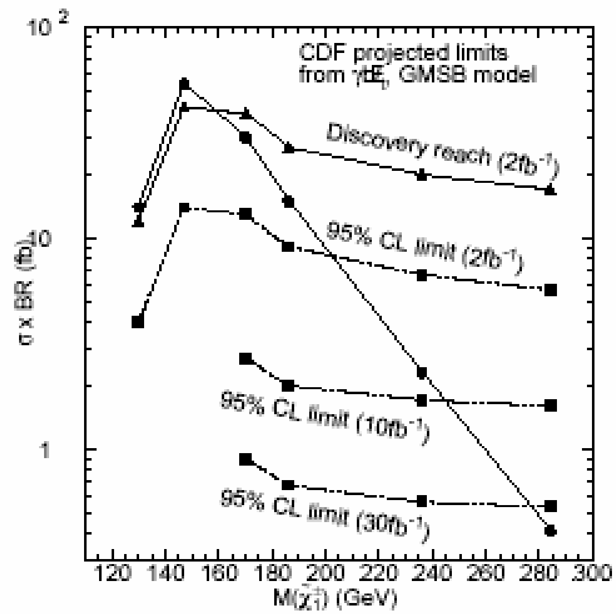
$M_{\tilde{\chi}^\pm} \sim 325$ GeV *(exclusion)* &

~ 260 GeV *(discovery)*

- Higgsino-like NLSP: $\tilde{\chi}_1^0 \to (h, Z, \gamma)\tilde{G}$

  Signal: γ b $\not\!\!E_T X$

  diboson signatures $(Z \to \ell\ell/\mathrm{jj};\ h \to b\bar{b})\not\!\!E_T$



$M_{\tilde{\chi}_1^\pm}$ sensitivity up to 200 GeV for 2 fb^{-1}

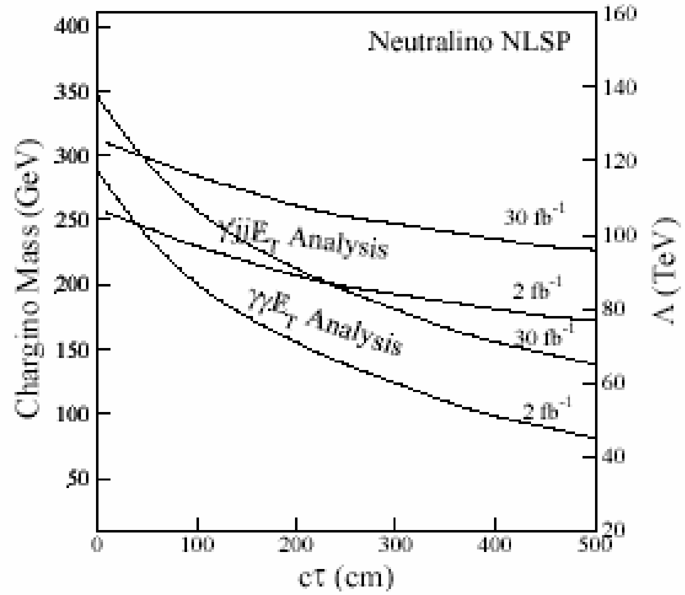
- Non-prompt Decays

  - Few 100 TeV $\leq \sqrt{F} \leq$ few 1000 TeV

– Bino-like NLSP

Photon Pointing: it is possible to identify a displaced photon from a secondary vertex and possibly det. decay length using TOF

Meas. of decay length $\rightarrow$ meas. of SUSY breaking scale



– Higgsino like-NLSP

$\Longrightarrow$ displaced γ's or secondary vertices from $b\bar{b}$, jj, $\ell^+\ell^-$

Search for displaced Z's using large E_T displaced jet with finite impact parameter or diplaced l's should be explored.

- If $\sqrt{F} \geq$ few 1000 TeV $\Longrightarrow$ outside detector decay looks like traditional $\tilde{\chi}_1^0$ LSP